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# Active and Reactive Power Regulation in Grid-Connected PV Systems

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**Abstract** — The high incidence of non-programmable renewable sources and in particular of photovoltaics can create relevant problems on distribution networks. These problems are mainly related to the uncertainty of the solar resource and the fact that photovoltaic systems do not take part in the essential network services. CEI 0-21, Italian technical standard, modifying the conception of the PV system, introduces important changes regarding services of frequency and voltage regulation for systems with rated power greater than 3 kW. In this paper, algorithms for voltage and frequency regulations are developed according to the prescription of CEI 0-21. They, along with a detailed model of a photovoltaic system, allow to study the impact of renewable sources on the distribution networks and the interaction of grid connected systems with the grid in the presence of over/under-voltage or over-frequency phenomena. Both algorithms have been tested numerically and results are reported

**Keywords**— Active Power Regulation; Reactive Power Regulation; Grid Connected PV System;

## I. INTRODUCTION

Since a decade now, in the world, a huge spread of production units fueled by renewable sources not programmable occurred. In Italy, between 2011 and 2012, there was a large increase in installation of photovoltaic systems due to an important incentive policy implemented by the government.

In a few years, a very rapid transformation from centralized generation system to distributed generation system is occurred.

This has caused problems difficult to solve in the distribution networks as the deterioration of voltage profiles along the lines, accidental disconnection of the interface protection systems of the inverter, problems of stability to the electric system. The reasons of these problems are to be found mainly in the non-adjustment of the distribution lines, in the role played by grid connected PV system and in uncertainty of renewable sources.

Conventional PV system only supplies the instantaneous maximum power from PV array to the grid through an inverter. Distribution companies cannot directly control distributed generators, and this makes the availability of electricity produced by GD plants an unknown variable difficult to estimate.

With the standard CEI 0-21 the conception of the grid connected plants has been modified. Photovoltaic systems are transformed into an "active" components of the power system and must be capable of delivering essential grid services such as the voltage and frequency regulations.

These services are essential to the proper functioning of the electrical system and are the starting point for an ever stronger of distributed generation in the conventional generation system.

In literature there are not many papers about active and reactive power regulation in grid connected PV system.

Almost all studies are conducted on PV plants with unity power factor and for this reason only few articles focus attention on the limitation of voltage fluctuations at point of common coupling by means the regulation of reactive power [1] [2] [3] because in many cases over-voltages are damped by limiting the active power fed into the grid.

To perform active power regulation in grid connected PV system three approaches have been proposed: 1) using an energy storage system while keeping the PV system to work in the MPP [4] [5]; 2) using a damp load bank to absorb surplus energy produced by PV plant [6]; 3) change the converter control strategy to modulate the power extracted from the PV array [7] [8] [9].

The latter approach is certainly the most economical because it does not require any additional component.

The aim of this paper is the development of algorithms for voltage and frequency regulation as prescribed by the standard CEI 0-21. These algorithms combined with a detailed model of the grid connected PV system allow to study the interaction of grid connected systems with the grid in the presence of over /under-voltage or over-frequency.

This paper is organized as follows: 1) the model of grid connected PV system is briefly described; 2) the mechanisms of the voltage and frequency regulation have been discussed in detail; 3) the mode of operations of voltage and frequency regulation are analyzed. Voltage regulation has been implemented through two standard characteristic:  $\cos\phi=f(P)$  and  $Q=f(V)$ ; 4) the implementation of voltage and frequency regulation algorithms is shown.

Finally, the control algorithms developed were tested numerically to verify the operation complies with CEI 0-21.

## II. GRID CONNECTED PV SYSTEM MODEL

Fig.1 shows the block diagram of grid connected PV system.

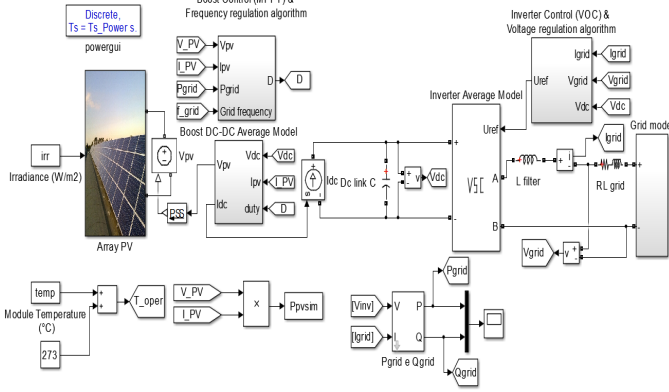


Fig. 1. Block diagram of the AC part of the grid connected PV system

It consists of 4 main parts:

- PV array: it is modeled using the Modified PLPB technique. In this way a substantial reduction of simulation time is obtained [10].
- dc/dc boost converter modeled: it is modeled using an average model to increase the speed of the model [10]. It tracks the MPP under normal condition while modulates the PV array power when an over-frequency occurs.
- single phase dc/ac converter: it produces sinusoidal ac current and voltage output whose magnitude and frequency can be controlled. Under normal condition the control strategy of inverter determines: 1) the level of the active power injected into the grid; 2) the synchronization of the inverter; 3) the connection to the grid [11]. When an over/under voltage occurs, the inverter control strategy acts on adjustment of reactive power flow.
- The grid

## III. VOLTAGE AND FREQUENCY REGULATIONS

### A. Decoupling of control channels

The study of voltage and frequency regulation is quite complex. Considering the h-th node of a generic network, its complex power  $S_h$  is [12]:

$$\begin{aligned} \bar{S}_h &= P_h + jQ_h = \sqrt{3}\bar{V}_h\bar{I}_h^* = \\ &= \bar{V}_h[\sum_{k=1}^N (G_{hk} + jB_{hk})^* \bar{V}_k^*] \end{aligned} \quad (1)$$

where:

$$\begin{cases} \bar{V}_h = V_h e^{j\theta_h} \\ \bar{V}_k = V_k e^{j\theta_k} \end{cases} \quad (2)$$

Substituting (2) into (1), after simple steps  $S_h$  becomes:

$$\bar{S}_h = V_h[\sum_{k=1}^N V_k (G_{hk} - jB_{hk}) [\cos(\theta_{hk}) + j \sin(\theta_{hk})]] \quad (3)$$

From (3), separating real from imaginary part, the active and reactive power flows along a line connecting the node h to a generic node k can be expressed as follows:

$$P_{hk} = V_h V_k [(G_{hk} \cos(\theta_{hk}) + B_{hk} \sin(\theta_{hk}))] \quad (6)$$

$$Q_{hk} = V_h V_k [(G_{hk} \sin(\theta_{hk}) - B_{hk} \cos(\theta_{hk}))] \quad (7)$$

Performing the partial derivatives of (6) and (7) with respect to the variable  $V_h$ ,  $V_k$ ,  $\theta_h$  and  $\theta_k$  it is possible to evaluate the dependence of active and reactive power from voltage and frequency. For HV overhead lines, generally, the phase shift between the voltages at the beginning and at the end of the line is very small and the conductance G can be neglected compared to susceptances B. Under this assumptions, under static operation, the frequency regulation can be performed by acting only on the active power while the voltage regulation can be carried out by adjusting the reactive power.

This statement is not entirely true for LV lines and then there is a coupling between the control channels of voltage and frequency. Generally the active and reactive power impacts on node voltage in a LV lines is almost the same. In particular, for overhead lines the reactive powers impacts on node voltage is greater than that of active power while in underground cable lines the opposite occurs [13]. The standard CEI 0-21 prescribes that PV plants have to perform voltage regulation by regulating reactive power. When the adjustment of active power is not sufficient to keep the voltage of the node below the 110% of  $V_n$ , the active power injected into the network is limited.

Frequency regulation is less critical then voltage regulation because grid frequency is very sensitive to variation of the active power and less sensitive to those of reactive power. For this reason standard CEI 0-21 decrees that the frequency regulation has to be performed acting only on the active power injected into the grid.

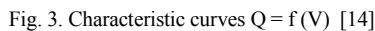
### B. Voltage regulation

CEI 0-21 decrees that all grid-connected PV plants with a power rating ( $P_n$ ) greater than 3kW have to provide the voltage regulation service through the injection of positive or negative reactive power. The reactive power is used to limit the over/under voltages caused by the PV plant during the injection of active power into the grid. The inverters used in these plants have to be capable of delivering reactive power automatically, in local control logic, according to two characteristics. The power factor of the PV grid connected plants, and then the reactive power delivered or absorbed, can be a function of the active power injected into the grid ( $\cos\phi = f(P)$ ).

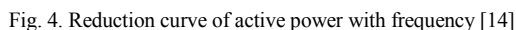
Upon exceeding the working point  $P/P_n = 0.5$  (curve a) type), or  $P/P_n = 0.05$  (curve b) type), the inverter occurs if the voltage at its terminals, called voltage at point of common coupling  $V_{pcc}$ , is greater than the value "critical" for the Lock-In. Generally Lock-In value is equal to  $1.05V_n$  for over-voltages and  $0.95V_n$  for under-voltages. If this check is positive, the voltage regulation is activated according to the profile shown in Fig. 2, otherwise the inverter continues to provide power with a unity power factor.

Figure 1 is a graph showing the characteristic curves of the power factor  $\cos \varphi$  as a function of the normalized active power  $P/P_n$  for two types of loads. The y-axis represents  $\cos \varphi$  with values 0.9, 0.95\*, and 1. The x-axis represents  $P/P_n$  with values 0, 0.2, 0.5, and 1. The graph is divided into two regions: 'inductive' (top) and 'capacitive' (bottom). The 'No regulation zone' is indicated for  $P/P_n > 0.5$ . The curves are labeled 'characteristic curve, type a)' and 'characteristic curve, type b)'. The legend indicates that the hatched area represents 'type a)' and the cross-hatched area represents 'type b)'. The curves are defined by the points A, B, and C, with the condition  $A = B = 0.05$ .

Voltage regulation in PV plants with  $P_n > 6\text{kW}$  can be performed, according to the distributor's prescription, by means of a characteristic curve ( $Q=f(V)$ ) dependent on the value of voltage at the point of common coupling  $V_{\text{pcc}}$  (Fig.3). When  $V_{\text{pcc}} > V_{\text{IS}}$ , or  $V_{\text{pcc}} < V_{\text{LI}}$ , the inverter checks whether the active power supplied is greater than the threshold value of Lock-In (generally equal to  $0.2P_n$ ). If this check is positive, the regulation is activated; otherwise, the machine continues to provide active power with a unitary power factor until the power output remains below the lock-in limit. The regulation ceases when the active power falls steadily below the value of lock-out of power, equal to  $0.05 P_n$ , or when the grid voltage returns into the range  $[V_{\text{IS}}, V_{\text{LI}}]$ .



CEI 0-21 establishes that when a frequency transient occurs, the injection of active power into the grid has to be adjusted in accordance with the characteristic of Fig. 4.



When the grid frequency exceeds the threshold of 50.3 Hz, grid connected PV plants have to reduce the active power,  $P_{\text{imax}}$ , injected into the grid according with the regulation statism and the value of over-frequency. When the grid frequency decreases, the power injected into the grid has to be limited to the limit value reached during the over frequency transient, until the frequency is in the range  $50 \pm 0.1$  Hz for 300 seconds continuous.

#### IV. MATLAB/SIMULINK MODELS

To control separately the active and reactive power an inverter control strategy called Voltage Oriented Control (VOC) has been implemented [11]. This strategy works on a d-q grid voltage synchronous rotating reference frame. The voltage regulation is performed by controlling the reactive power and for this reason the classic VOC has been modified, by adding a control loop which generates the reference of reactive power, and then the reference current of the q axis,  $I_{q\_ref}$ .



The Simulink diagram of the algorithm for voltage regulation by the characteristic power factor =  $f(P)$  is shown in Fig. 7.

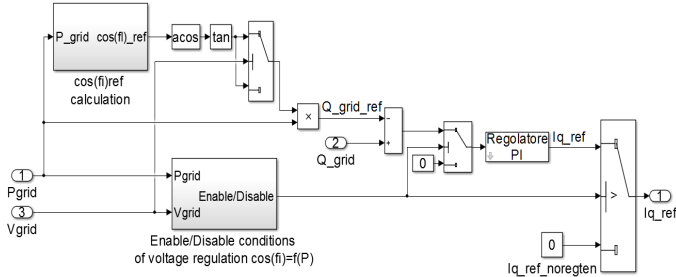


Fig. 7. Simulink Model of Voltage Regulation Algorithm  $\cos\phi=f(P)$

The scheme consists of two main blocks: the first performs the calculation of the power factor as a function of the value of active power injected into the network through of the characteristic type a) seen previously in Figure, while the second determines the conditions of activation and deactivation of voltage regulation (Fig. 7.).

The diagram Simulink algorithm developed to implement voltage regulation according to the characteristic  $Q = f(V)$  is shown in Fig.8.

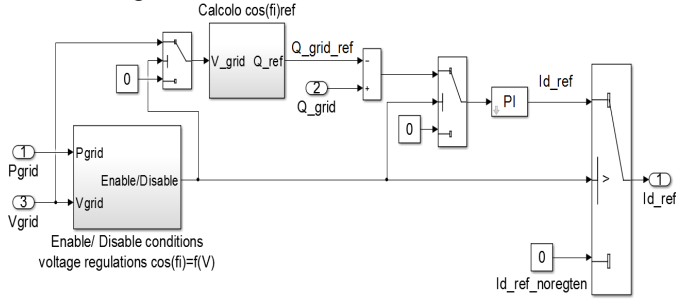


Fig. 8. Simulink Model of Voltage Regulation Algorithm  $Q=f(V)$

### B. Frequency regulation model

Frequency regulation, unlike that voltage regulation, is carried out by adjusting the active power supplied by the PV systems, acting on the boost converter. Active power control is performed through the dc-dc converter by changing the operating point of the PV array in order to extract only the necessary power. The boost converter, which is generally used for the track of the maximum power point, in this case has to be controlled either by the MPPT and by means of frequency control algorithm. Therefore a system for control of the boost converter which alternates, depending on the value assumed by the mains frequency, the tracking of the MPP and the frequency regulation has been developed.

Fig.9 shows the Simulink block diagram of MPPT/frequency control algorithm. It consists of seven main block:

- Block 1 performs the switch between the MPPT and the frequency regulation algorithm;
- Block 2 implements the above mentioned algorithms;
- Block 3 implements the activation conditions of the frequency regulation, performs the calculation of the  $P_{imin}$  and generates the reference profile of power to be imposed to the dc-dc converter when an over-frequency occurred;

- Block 4 generates the reference profile of power to restore the power  $P_{imax}$  after the extinction of over-frequency transient;
- Block 5 generates the reference profile of the power to adjust the supply of active power to the maximum available level;
- Block 6 performs the switch between the reference profiles of power generate by the block 3, 4 and 5;
- Block 7 implement the deactivation conditions of frequency regulation.

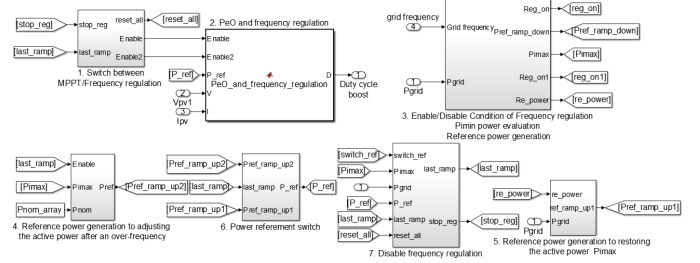


Fig. 9. Simulink Model of Frequency Regulation Algorithm

## V. SIMULATION RESULTS

To verify if the developed voltage and frequency regulation algorithms re in accordance with standard CEI 0-21, various simulations have been performed. In the voltage regulation through the characteristic curve  $\cos\phi=f(Q)$ , the power factor does not depend directly on the value assumed by the voltage  $V_{pcc}$  but by the value of the nominal power fed into the grid. The dependence on the voltage  $V_{pcc}$  is still present because, as is known, when the system delivers power, the voltage of the injections node tends to increase.

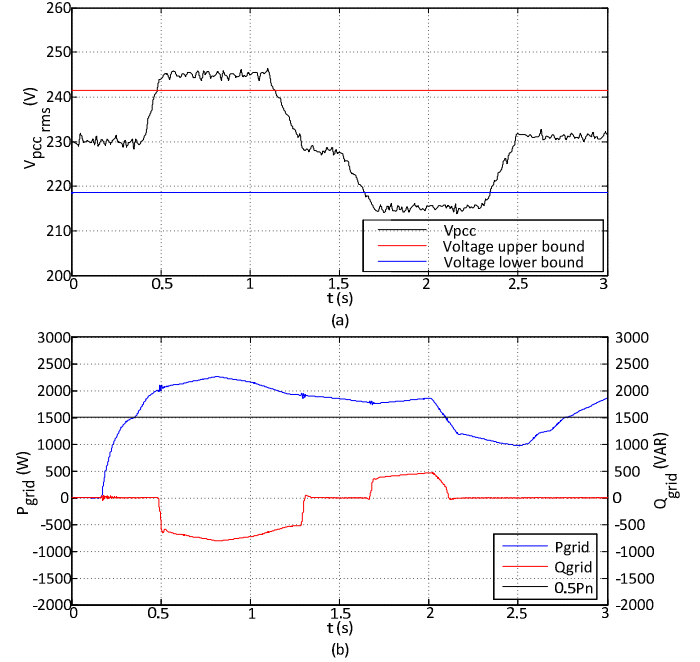


Fig. 10. Voltage regulation  $\cos\phi=f(P)$  for 3kW PV plant: (a) voltage  $V_{pcc}$ , (b) active and reactive power injected into the grid



Fig. 10 shows that the quantity of reactive power fed into the grid depends exclusively on the value of the active power supplied by the plant. In fact, maintaining the irradiance on the entire subtring uniform and constant, it is possible to observe that when the amplitude of the mains voltage goes out of range [218.5-241.5], the system begins to deliver or absorb a quantity of reactive power proportional the active power fed into the grid.

Considering the voltage regulation according to the characteristic curve  $Q = f(V)$ , the value of the reactive power injected or absorbed by the network depends exclusively on the value of voltage  $V_{pcc}$ .

Fig. 11 shows the link between the line voltage and reactive power fed into the grid. In fact as soon as the supplied active power exceeds  $0.2 P_n$ , if the mains voltage is outside the range of values  $[0.92V_n, 1.08V_n]$ , the voltage regulation is enabled.

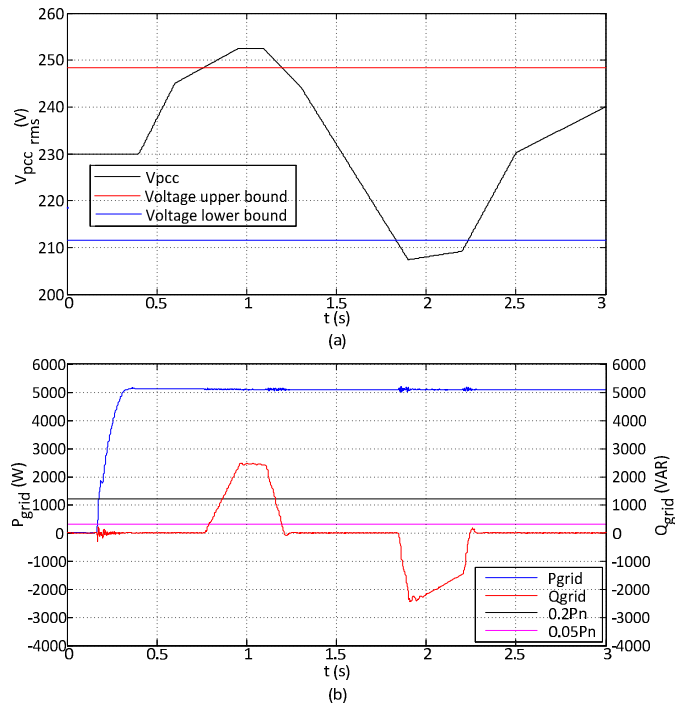


Fig. 11. Voltage regulation  $Q=f(V)$  for a 6 kW PV plants, (a) voltage  $V_{pcc}$ , (b) active and reactive power injected into the grid

The following case studies refer to the operation of the frequency regulation under two different conditions.

In the first case study (Fig.12) uniform irradiance condition is considered. When the value of the grid frequency exceeds 50,3Hz the frequency regulation is enabled and the value of active power delivered when the over frequency occurred ( $P_{imax}$ ), is stored. Using the power  $P_{imax}$ , the statism set ( $83.3\% P_n / \text{Hz}$ ) and the maximum value assumed by the grid frequency during the over frequency transient, the value of active power ( $P_{imin}$ ) that has to be delivered by the system following the over frequency is calculated.

The developed algorithm controls the boost and brings the system to work, in a linear way, in correspondence of the value  $P_{imin}$ . Despite at the time  $t=0.8$ s the frequency decreases, the system continues to deliver the power  $P_{imin}$  because to turn off the regulation, the frequency has to return for 300 seconds

continuous (1s in simulation) in the range  $50 \pm 0.1\text{Hz}$ . At time  $t = 1$ s, the frequency increases again to reach a new maximum, and then the control algorithm evaluates the new power  $P_{imin}$  and controls the boost in order to adjust the supply of active power. At the time instant  $t=1.3$ s, the frequency starts to decrease and at time  $t = 1.48$ s returns to below 50.1Hz. After 300 s (1s in simulation) the level of power delivered before over frequency is re-established with a gradient of  $20\% P_{imax} / \text{min}$ . Once restored the power value  $P_{imax}$ , the regulation stops and the MPPT algorithm is enabled. The over frequency transient that starts at  $t = 4.6$ s shows what happens when the frequency returns below the 50,1Hz for a period of time insufficient to deactivation of frequency control.

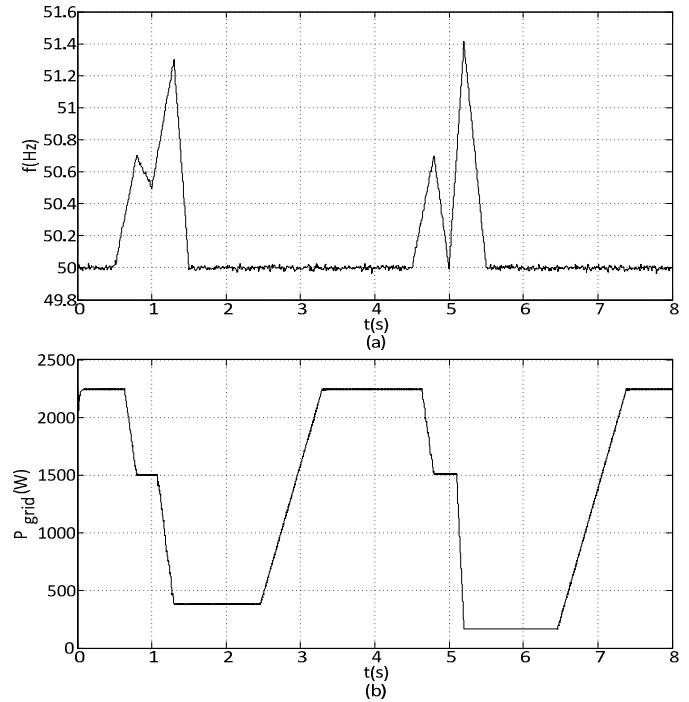


Fig. 12. Case study 1: Frequency regulation, (a) grid frequency, (b) active power injected into the grid

In the second case study the radiation incident on the photovoltaic system, and therefore the power, are not maintained constant (Fig. 13). In particular, the power produced by PV is varied sharply during the adjustment of frequency to ensure that the system continues to work as it should. At time  $t = 0.7$  s, the irradiance decreases sharply to a value such that the maximum output power from the plant is less than the value  $P_{imin}$  calculated following the over frequency. In this case, as can be seen in the figure, the algorithm developed controls the boost so as to extract the maximum power available from the array (obviously lower than  $P_{imin}$ ). At time  $t=1$ s there is a further increase in frequency and then the value of  $P_{imin}$  is updated. When it becomes less than the maximum power output from the array PV, the control algorithm provides to adapt the active power by engaging the reference signal imposed. When the grid frequency returns at below the 50,1Hz for 1s, the algorithm starts dispensing active power with a gradient of  $20\% P_{imax}/\text{min}$ . During the adjustment phases, the irradiation is

increased and assumes a value such that the maximum output power from the array becomes higher than that the power delivered at the time of over-frequency,  $P_{imax}$ . Therefore, after restoring the power  $P_{imax}$ , the algorithm adjusts the power delivery to the new level of available power with a gradient of 20%  $P_{nom}/min$ , and then it turns off. At time  $t = 4.7$  s a new over frequency transient occurs and it is perfectly handled by the developed control algorithm.

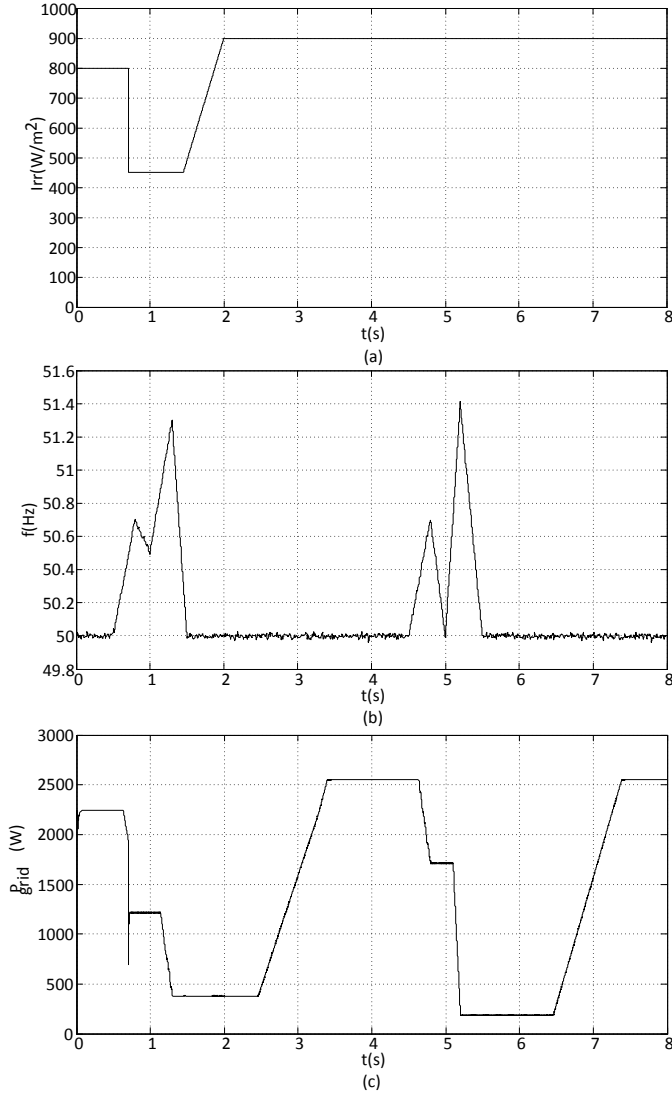


Fig. 13. Case study 2: Frequency regulation (a) irradiance on PV array surface, (b) grid frequency, (c) active power injected into the grid

## VI. CONCLUSION

The main objective of this paper was the development of voltage and frequency regulation algorithms according to the prescription of the Italian technical standard CEI 0-21. These algorithm allows to study the impact of regulations on distribution network and on PV systems. Both algorithms were tested by means of simulations to verify correct operation and observing results obtained, it is possible to infer that the algorithms developed can perfectly follow the dictates imposed by CEI 0-21. Based on these possible it is possible to study a local grid or isolated grid in presence of an high concentration of PV systems under contingencies that create frequency and voltage disturbances.

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